NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2759

WEAR AND SLIDING FRICTION PROPERTIES OF NICKEL ALLOYS SUITED FOR CAGES OF HIGH-TEMPERATURE ROLLING-CONTACT BEARINGS

II - ALLOYS RETAINING MECHANICAL PROPERTIES ABOVE 600° F

By Robert L. Johnson, Max A. Swikert
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Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

Wear and sliding friction properties of a number of nickel alloys operating against hardened SAE 52100 steel were studied. The alloys were cast beryllium nickel, heat-treated beryllium nickel, cast Inconel, Nimonic 80, Inconel X, Refractalloy 26, and Discaloy. Some of the alloys studied may be useful as material for cages of rolling-contact bearings that operate at high speeds with temperatures above 600° F in projected aircraft turbine engines or for bearings that operate in corrosive mediums.

Desirable operating properties and the absence of extreme mass welding of all the materials studied could be associated with the development on the sliding surfaces of a naturally formed film of nickel oxide. On the basis of wear and friction properties, cast Inconel performed very well in these experiments and compares favorably with nodular iron. Nimonic 80 also showed promise as a possible cage material.

INTRODUCTION

As discussed in considerable detail in references 1 to 4, cages (separators or retainers) have been the principal source of failure in rolling contact bearings of aircraft turbine engines. These failures are generally lubrication failures and occur at the cage locating surfaces, as indicated in figure 1. One approach to this problem involving the use of materials with inherent "antiweld" characteristics is discussed in reference 1. In general, the materials of reference 1 do not have satisfactory mechanical properties for cage materials at temperatures greater than 600° F. Other nickel alloys, however, show good combinations of high strength and corrosion resistance at elevated temperatures. For these alloys, however, no data are available (even at room temperature) on their surface failure or surface welding properties under extreme sliding conditions. An investigation was therefore conducted to determine the friction, wear, and surface failure properties of a number of nickel alloys which had good mechanical properties at temperatures above 600° F. This research was conducted at the NACA Lewis laboratory on sliding friction apparatus to obtain fundamental comparative information on the various materials. The experiments were not intended as simulated cage tests.

The friction and wear experiments were conducted with loaded hemispherically shaped specimens with different nickel alloys sliding in a continuous path on rotating steel disk specimens at room temperature. Most experiments were run at a sliding velocity of 5000 feet per minute with loads from 50 to 1593 grams. Wear debris was studied by means of X-ray diffraction techniques. The nickel alloys studied included (in order of decreasing nickel content) cast beryllium nickel, heat-treated beryllium nickel, cast Inconel, Nimonic 80, Inconel X, Refractalloy 26, and Discaloy. Data for "L" nickel are also included as a standard for comparative purposes only.

MATERIALS

The materials used in this investigation were selected because they have adequate mechanical properties at temperatures above 600° F. The materials studied, their compositions, and some of their typical properties are listed in table I.

Although most of the values reported in table I are published data, the hardnesses were found comparable with data obtained with the Rockwell superficial hardness tester. Initial surface-roughness values for the disks were obtained with a profilometer. The properties of L-nickel were obtained from reference 5 and other International Nickel Company Inc. publications. Data on beryllium nickel were obtained from The Beryllium Corporation. The properties of Nimonic 80 were obtained from The General Electric Company, while the data on Refractalloy 26 and Discaloy were obtained from Westinghouse Electric Corporation and other sources.

The photomicrographs (X100) of metallographic specimens of the alloys used in the friction and wear experiments reported herein are shown in figure 2. These photomicrographs show the types of structure and the relative grain sizes of the alloys investigated.

The experiments were run with SAE 52100 steel (hardness, Rockwell C60 to 62) as the disk specimen even though this steel is unsatisfactory for operation at high temperatures. The high-speed tool steels (18-4-1 and molybdenum types) have appreciable promise for rolling-contact bearings to operate at high temperatures because of the combination of hot hardness and relatively good fatigue strength; these steels were, however, not available in sizes required for the disk specimens of these experiments in time for this investigation. Indications are that the results with the tool steels of hardnesses equal to that of SAE 52100 would not be appreciably different from those obtained in the majority of these experiments. The thermal expansion coefficients of two tool steels are shown in table I for comparison with the coefficients of the materials of this investigation.

APPARATUS AND PROCEDURE

Specimen preparation. - In each experiment there were two specimens, the rider and the disk. The rider specimens, of the materials being investigated, were cylindrical (3/8-in. diam, 3/4-in. length) and had a hemispherical tip (3/16-in. rad.) on one end. The surface of the rider specimens was finished by fine turning; minimum material removal per cut was used in order to minimize surface cold working. The disk specimens (13-in. diam.) were circumferentially ground on a conventional surface grinder with light grinding pressures to produce a surface roughness of 10 to 15 rms as measured with a profilometer. These values of roughness are within the range of roughness measurements obtained on cage locating surfaces of representative rolling-contact bearings (reference 6).

The rider specimens were cleaned before each experiment with a clean cloth saturated with redistilled 95-percent ethyl alcohol. The disk specimens were carefully cleaned to remove all grease and other surface contamination according to the detailed procedure given in reference 7. Briefly, this cleaning procedure includes scrubbing with several organic solvents, scouring with levigated alumina, rinsing with water, washing with ethyl alcohol, and drying in an uncontaminated atmosphere of dried air.

Friction apparatus. - The friction apparatus used for these experiments is essentially the same as that described in reference 7. A diagrammatic sketch of the apparatus showing the holder assembly for the rider specimens and the rotating disk specimens that are the primary parts is presented in figure 3. The disk is rotated by a hydraulic motor assembly that provides accurate speed control over a range of sliding velocities of 75 to 18,000 feet per minute. The disk specimen was mounted on a flywheel assembled with its shaft supported and located by a mounting block which contained bearing assemblies for accurate location. Loading was accomplished by placing weights on the axis of the rider holder. Friction force was measured by four strain gages mounted on a beryllium-copper dynamometer ring and connected to an observation-type potentiometer converted for use as a friction-force indicator. The strain gages were so mounted that temperature compensation was obtained. The coefficient of friction μ_k is calculated from the equation

$$\mu_k = \frac{F}{P}$$

where F is the measured friction force and P is the applied normal load. The reproducibility of the coefficient of friction values in all but isolated cases was within ± 0.04 for dry surfaces and within ± 0.02 for lubricated surfaces. The data presented are complete data from a representative experiment on each material under the specified conditions.

Friction-force readings are recorded by a motion-picture camera (64 frames/sec) timed to operate for 3 seconds covering each separate friction run.

Method of conducting experiments. - Wear runs of 3 hour duration were made on dry surfaces with loads of 50 and 269 grams at a sliding velocity of 5000 feet per minute. All runs were made at room temperature. The complete run was made over the same wear track (without radial traverse of the rider specimen). Wear of the rider was determined at regular intervals from measurements of wear-spot diameter made with a calibrated microscope and by weight loss obtained with an analytical balance. The final wear-volume measurements could generally be reproduced within ± 10 percent in different experiments on a given material. Weight loss measurements were used as a rough check on the accuracy of the wear-spot-diameter area. No wear measurements were made of the slider (disk) specimen.

Friction runs to determine effect of loading were made with boundary-lubricated surfaces at a sliding velocity of 5000 feet per minute with increasing loads in increments from 119 grams to the failure point of the specimens. The disk was lubricated before each 3-second run by rubbing a very thin film of a petroleum lubricant grade 1005 (Air Force specification 3519, Amendment 2) on the rotating surface using lens tissue. Previous experience at this laboratory has indicated that the film formed by this procedure is sufficiently thin that hydrodynamic lubrication will not occur. Reference 8 shows that a lubricant film of this type may approach a monomolecular film at the points of the surface asperities. Surface failure was established by both increased friction values and the occurrence of welding (visible metal transfer).

The loads and the specimen shapes were so chosen as to produce relatively high initial surface-contact stresses. In spite of the relatively light loads and large apparent areas of contact of the cages at their locating surface in rolling-contact bearings under normal conditions, the actual contact stresses can be large. As discussed in more detail in reference 9 (pp. 10-32), surfaces under nominal load and with large apparent areas of contact can have stresses at the localized contact areas that are equal to the flow pressure (compressive yield strength) of the materials.

RESULTS AND DISCUSSION

As discussed in more detail in reference 1, for possible cage materials the surface failure properties are of greater importance than the friction properties although these factors are somewhat related. The first stage of surface failure is the incipient breakdown of the fluid lubricant, and the second stage is the contact of metals free of fluid lubricant. This condition increases the severity of temperature flashes which increases the susceptibility of the metals to surface adhesion. Subsequently, incipient surface failure occurs; this condition is usually detected by increased friction and by the appearance of minute surface welds. The ultimate point of failure is complete seizure or mass welding of the surfaces. Surface temperatures that accompany mass welding are generally extremely high (approaching the melting point) and may result in the welded junctions having such low shear strength that there is little or no increase and possibly a decrease in friction. The presence of a naturally formed reaction film such as an oxide may generally arrest the progression of surface failure.

Because of the importance of surface failure, particular effort was made in the studies described herein to detect its occurrence. Study of the rates of wear and the appearance of the surfaces generally made it possible to establish the initial occurrence of mass surface failure.

Wear of unlubricated surface. - The data of figure 4 show the total wear volume at different time increments up to 3 hours for each material at a sliding velocity of 5000 feet per minute with loads of 50 (fig. 4(a)) and 269 (fig. 4(b)) grams. At the light loads (fig. 4(b)) annealed "L" nickel (which is included as a standard for comparison purposes only) had good wear properties. At the heavier loads (fig. 4(b)), however, annealed "L" nickel had more wear than cast Inconel. Table II shows the wear for all the materials studied as ratios of the total wear to that for "L" nickel; these ratios are based on data taken from figure 4. Table II also summarizes film-formation and surface-failure properties of the materials of this investigation; these properties will be described in detail as the individual materials are discussed. The wear data of figure 4 show an appreciable effect of load on the relative wear rates of the different materials. As discussed in more detail in reference 1, the large increase in wear for annealed "L" nickel with the heavier load is probably a result of low mechanical strength but the use of relations based on the physical properties of the materials will not explain the wear properties observed in these experiments.

As for the materials of reference 1, the surface-failure and wear properties of the materials of this investigation depended primarily on the film-forming properties of the materials, but the conditions of the wearing surface were changeable; films were continually forming, wearing away, and reforming, thus producing wear debris in the form of black powder. Similarly, the friction coefficients for these materials were for the most part quite changeable with the formation of surface films. In general, the initial dry friction values during the wear runs (0.25 to 0.35) were substantially higher than the subsequent values (0.10 to 0.15). The trend of reduced friction coefficient with continued running coincides with the formation of surface films and possibly cold working of the slider.

The data of figure 4 indicates that cast Inconel is one of the best of the materials, with Nimonic 80 showing good results also. Both materials showed appreciable film formation, which probably accounts for the good wear properties. Under all conditions both of these materials were also relatively free of welding. Cast Inconel and Nimonic 80 compare favorably from a wear standpoint with the best materials (nodular iron and gray cast iron) as illustrated by the data curves of reference 4. Cast Inconel and Nimonic 80, however, show appreciably lower friction than the irons of reference 4.

The wear curves for beryllium nickel (heat treated) and Discaloy at 269-gram load were especially checked for reproducibility to verify the shape of the curves.

Figures 5 and 6 are photographs of wear areas of several rider specimens after the dry wear runs (3 hr at 5000 ft/min) with loads of 50 (fig. 5) and 269 (fig. 6) grams. As indicated in figure 5(a) the "L" nickel appeared to have the best surface condition of all the materials in these experiments; it had a uniform black film on the wearing area with no sign of surface failure. There was an indication, however, of appreciable plastic deformation at the trailing edge of the slider of the wear area (bottom of photograph). The plastic deformation was probably the result of the low yield strength of the annealed "L" nickel. Cast Inconel (fig. 5(b)) and Nimonic 80 (fig. 5(c)), which have appreciably higher yield strengths than "L" nickel, did not evidence appreciably plastic deformation. Neither did they show as good film forming properties as "L" nickel, although surface films did form on the areas that appeared to be supporting the load. These areas also showed surface flow as illustrated by the fine lines normal to the direction of motion (fig. 5(c)).

The films formed on the wear areas of "L" nickel specimens run with a load of 269 grams (fig. 6(a)) were not as continuous as those formed with a load of 50 grams (fig. 5(a)). Mass welding was, however, effectively prevented.

Cast Inconel (fig. 6(b)) had the best surface condition as well as the least wear of any of the materials after wear runs at the heavier load. Surface flow lines were present over the entire wearing area of the specimen and since Inconel work hardens readily (reference 10) it is probable that the surface of this specimen was appreciably harder than indicated by the value given in table I. For a given material, work hardening of the surface might be beneficial with respect to reducing wear and friction. A surface film was present on most of the running area and appeared to be of a greater thickness in the area that was supporting the load.

The wear areas of the Nimonic 80 specimens (fig. 6(c)) were similar to those obtained with cast Inconel; the Nimonic 80 exhibited surface flow lines and nonuniform but fairly complete film formation. The films formed on the Nimonic 80 were, however, less uniform than those found on the cast Inconel specimens.

The wear tracks on the disk specimen shown in figure 7 are the surfaces against which the slider specimen areas of figure 6 were run. In general, the wear tracks on the disk specimen showed either a uniform smearing of transferred metal (fig. 7) or "globs" of welded metal from the rider specimens (not shown in fig. 7). The smeared surfaces were coated for the most part with the same naturally formed films formed on the rider specimens. Surface flow lines were common in the transferred metal. The disk specimen against which the "L" nickel rider specimen operated showed smeared transferred metal on which a dark film had been formed. The smeared films of Inconel and Nimonic 80 on the disk (fig. 7(b) and 7(c)) were somewhat less uniform than the smeared films obtained with "L" nickel, and they both showed surface flow lines not discernible on surfaces run with "L" nickel. None of the rider materials caused significant damage to the disk surfaces; the running surfaces on the disks were, in fact, formed by transferred rider materials. It was probably only because of the films formed on the surfaces that mass welding was not common to all the alloys of the investigation reported herein. At some time during the wear runs, beryllium nickel, Refractalloy 26, and Discaloy showed evidences of incipient failure.

Where surface photographs of materials are not included in this report the surface appearance of the specimens may be considered as being approximately represented by the figures that are included according to the comparisons given in table III.

Friction of lubricated surfaces. - It is under conditions of extreme boundary lubrication that the antiweld properties of the materials are most important. Consequently, a series of runs was made with all the materials under consideration sliding on boundary-lubricated disk surfaces; these results are presented in figure 8. The sliding velocity was deliberately chosen from reference 11 to be above the velocity (2500 ft/min) which results in film failure of the grade 1005 lubricant. In this manner, it was possible to insure that extreme boundary-lubricating conditions were obtained at the point of contact.

According to the data of figure 8, there is relatively little difference in friction coefficients of the various materials when they are operated under extreme boundary-lubricating conditions. As discussed in reference 1, the high friction coefficient of "L" nickel may have been the result of the extreme plastic deformation of the material which was taking place at the higher load. At the higher loads, generally, the friction coefficients for cast Inconel, Nimonic 80, Inconel X, Refractalloy 26, and Discaloy were independent of load. These materials have mechanical and chemical properties that are the least sensitive to changes in temperature. Increased loading would cause higher surface temperatures and, if physical properties of the surface material were essentially unchanged and mass welding did not occur, friction coefficients would also remain unchanged. Hardness was the principal physical property of interest in these experiments since the low shear strength of the surface as well as the inhibition of welding was probably provided by the surface films which formed during sliding.

In general, friction values are most affected by shear strength between the surfaces; the narrow range of friction values obtained with the high-temperature materials indicates that the surface films formed during sliding had approximately the same shear strengths. In all probability, therefore, the films are the same for all these materials. (This result is confirmed later).

The presence of a lubricant on the disk did not prevent the formation of surface films on the wear areas of the specimens. Several wear areas of rider specimens are shown in figure 9. As discussed in more detail in reference 1, annealed "L" nickel (fig. 9(a)) did not have sufficient yield strength to withstand the contact stresses imposed at the maximum load of 1593 grams. The appearance of the wear spot indicated that plastic flow of the surfaces had occurred; the presence of a film (which was apparent on the surface), however, prevented surface welding.

The cast Inconel (fig. 9(b)) had a uniform surface film with low wear and no sign of surface failure. Nimonic 80 (fig. 9(c)) had a continuous surface film on the wearing area, although this film was not as uniform as that on the cast Inconel. Nimonic 80 also had low wear and no sign of surface failure.

The other specimens of the experiments generally had surfaces less satisfactory than those exhibited by cast Inconel and Nimonic 80. The cast materials had surfaces similar to cast Inconel and the wrought materials had surfaces similar to Nimonic 80; the most apparent differences were the degree of film formation and the amount of wear. Further comparisons can be made by reference to table II.

X-Ray diffraction study of wear debris. - Specimens of the black powder formed during the wear runs with the nickel alloys were obtained from the disk surface as was done in reference 1. X-ray powder patterns were taken with a Debye-Scherrer camera using manganese radiation in order to determine for each material whether the wear debris formed was alloy, nickel oxide, or a combination of both. In figure 10(a) there is a comparison of the standard patterns of Inconel X, Nimonic 80, Refractalloy 26, and "L" nickel. The d values of the alloys approach the d values of face-centered cubic nickel. The slight variations were caused by the influence of the alloying elements in the space lattice of the nickel. Therefore, "L" nickel was used as a standard to compare with the d values of the debris. As is evident in figure 11(b), nearly all the wear debris patterns show d values corresponding to the standard pattern of "L" nickel. Other lines (d values) are apparent in many of the patterns. For example, d values of 2.06, 1.46, and 2.4 Angstrom units are positively identified. These lines correspond generally to the A.S.T.M. d values for nickel oxide NiO.

The patterns for the wear debris are therefore arranged in figure 11(b), in such a way as to be bracketed by the pattern for "L" nickel and nickel oxide.

Comparison of these patterns indicates that both the nickel oxide and the original alloy are present in the wear debris. The lines of nickel oxide corresponding to the d values of 2.07 and 1.27 Angstrom units in most cases cannot be distinguished from the lines of the standard alloy. Extra lines are observed in the wear debris pattern of "L" nickel, and may result from the different forms of the oxide.

The exact proportion of oxide to alloy could not be determined from these diffraction data but it was apparent that some of the wear debris samples contained more oxide than others. The most noticeable was the wear debris from "L" nickel. The diffraction pattern shows that it consists almost entirely of oxide. Of the other materials, cast Inconel showed the nickel oxide diffraction pattern most distinctly. As a general rule, it was found that the materials with the lowest wear rates were those which showed the highest proportion of oxide in the wear debris. This condition is consistent with the observed fact that the naturally formed oxide film is an effective solid lubricant which reduces wear and surface damage (reference 1).

Practical significance. - Consideration of all the data presented herein indicates that, of the materials included in this investigation, cast Inconel and Nimonic 80 are probably the most suited for sliding surfaces under either dry or extreme boundary-lubrication conditions. Cast Inconel consistently showed good sliding characteristics with little wear and no apparent surface welding. Under sliding conditions, the alloy readily forms an oxide film that reduces friction and prevents welding. Appearance of the wear areas on cast Inconel specimens indicates that considerable plastic flow of the surfaces occurred. Inconel cold works readily and it is possible that work hardening may contribute to the good friction properties of the material. The combination of a hardened surface with a low shear-strength surface film provides a desirable condition from a fundamental friction standpoint (reference 9, pp. 10-32). The performance of cast Inconel in these experiments compares favorably with that of nodular iron in the study reported in reference 4.

Thermal properties of cast Inconel make it appear attractive for use in high-temperature bearings; it has a coefficient of thermal expansion (table I) that is very close to that of steels. At the same time cast Inconel retains most of its room-temperature mechanical strength at temperatures to 1400° F (reference 5), and the film-forming properties that contributed to its effectiveness in these experiments could possibly be even more effective at higher temperatures.

The thermal properties of Nimonic 80 may also be acceptable for use in high-temperature bearings. Because its expansion coefficient of 7.34×10^{-6} is greater than that for steels, Nimonic 80 may be suited best for the inner-race riding cages of rolling-contact bearings.

The experiments reported herein indicate that the friction and surface-failure properties of the nickel alloys are dependent to a large extent on film-forming properties. Since formation of the oxide films is of value, the atmosphere which supplies the necessary oxygen for film formation is very important to the proper functioning of the material as slider surface. Caution therefore must be used in employing these materials for sliding surfaces designed to operate in inert or reducing atmospheres.

Since static-friction data have provided much of the basis for the generally poor opinion of nickel and nickel alloys as materials for sliding surfaces (reference 1), it may be desirable to avoid designs where the nickel alloys are allowed to operate initially in the clean or bare metal state against steel. Pretreatment of the contacting surfaces to form oxides on the nickel alloys might be necessary to insure against surface damage in the initial period of operation until the natural oxide films are formed.

Heat treatment of beryllium nickel had a very marked effect on the resistance to wear at light loads (fig. 4(a)). At the heavier load (fig. 4(b)), however, the effect was insignificant during much of the wear runs. The small effect at heavy load is believed to be a result of high surface temperature occurring during sliding, which probably exceeded the draw temperature and thus reduced the surface hardness. Because surface temperatures increase with load to values approaching the melting point of the material, it is probable that similar results could be obtained at increased loading with many heat-treated metals. Materials with the highest draw temperatures and the lowest friction coefficients will provide the most satisfactory sliding surface when heat treatment is used.

The data of these experiments do not make it possible to arrive at any conclusion regarding the effect of metallurgical structure on wear and friction properties. With materials having similar compositions, however, cast alloys performed in a manner superior to the wrought alloys.

Preliminary experiments at room temperature with several materials of this investigation sliding against disk specimens of 18-4-1 tool steel showed the same general trend obtained with disks made of SAE 52100 steel having similar hardness.

All the data reported herein were obtained at room temperature; however, the general trends observed (particularly the surface welding and friction properties) indicate what might be expected at the temperatures of interest. Reference 9 (p. 152) indicates that friction is affected only slightly by temperatures even as high as 1000° C. The mechanical strength and chemical (for example, oxidation) behavior of the materials of this investigation (both disk and rider specimen) are not significantly affected by the temperatures considered.

CONCLUDING REMARKS

Investigation of wear, friction, and surface-failure properties of dry surfaces and of friction and surface-failure properties of boundary-lubricated surfaces of cast Inconel, wrought Inconel X, Nimonic 80, Refractalloy 26, Discaloy, beryllium nickel, and heat-treated beryllium nickel sliding on hardened SAE 52100 steel were conducted at room temperature. The research showed that:

1. Desirable operating properties of all the materials studied was associated with the development on the rider surface of a naturally formed dark film identified by X-ray diffraction as being predominantly nickel oxide.

These results confirmed earlier results with other nickel alloys. It is probable that these films prevented mass surface welding with all material combinations of this investigation. High-temperature operation in air would accelerate the formation of the beneficial surface film. A pretreatment to form a surface film before operation would probably be of value.

2. Cast Inconel was the best material in most of the experiments performed. It was not subject to surface failure at the most severe conditions and evidenced desirable low wear characteristics. It has good

high-temperature physical properties, and a coefficient of thermal expansion that approaches that for steels. These properties make cast Inconel appear attractive for cages of rolling-contact bearings.

3. Nimonic 80 was one of the better materials under all types of operation. Because its thermal expansion coefficient of 7.34×10^{-6} is greater than that for steels, Nimonic 80 may be best suited for inner-race riding cages of rolling-contact bearings.

4. Cast Inconel and Nimonic 80 have wear properties comparable to and friction properties lower than the cast irons previously described.

5. Beryllium nickel, Refractalloy 26, and Discaloy showed signs of incipient failure at some time during the wear runs.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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TABLE I - TYPICAL VALUES FOR PROPERTIES OF MATERIALS

Material	Nominal composition (percent)	Tensile strength (lb/sq in.)	Yield strength (lb/sq in.)	Brinell hardness	Modulus of elasticity	Density (lb/cu in.)	Coefficient of thermal expansion (in./in./°F) (a)	Coefficient of thermal conductivity (Btu/(sq ft)(hr)(°F/in.))	Melting point (°F)
"L" nickel (annealed)	99.4 Ni 0.02 C(max) .1 Cu .15 Fe .05 Si .2 Mn	60×10^3 (57×10^3 at 600° F)	15×10^3 (13×10^3 at 600° F)	90	30×10^6	0.321	7.2×10^{-6} (32°-212° F)	420	2625
Inconel (cast)	77.75 Ni 13.5 Cr 6.0 Fe 2.0 Si	85×10^3 (60×10^3 at 600° F)	40×10^3 (26×10^3 at 500° F)	175	23×10^6	0.300	6.4×10^{-6} (32°-212° F)	[c]104 (32°-212° F)	2525
Inconel X (wrought)	73.0 Ni 15.0 Cr 7.0 Fe 2.5 Ti	180×10^3 (154×10^3 at 600° F)	120×10^3 (88×10^3 at 800° F)	360	31×10^6 (28.7×10^6 at 500° F)	0.300	7.6×10^{-6} (32°-212° F) 8.0×10^{-6} at 100°-800° F)	102 (32°-212° F) (140 at 572° F)	2570
Nimonic 80 (wrought)	74.2 Ni 21.2 Cr 2.4 Ti .6 Al .5 Si .04 C .6 Mn	153×10^3 (97.5×10^3 at 1200° F)	83.8×10^3 (77×10^3 at 1200° F)	[b]176	31.4×10^6 (27.6×10^6 at 932° F)	0.296	7.33×10^{-6} (70°-600° F)	86 at 212° F	----
Refractalloy 26 (wrought)	37 Ni 3 Mo 18 Fe 2.8 Ti 18 Cr .2 Al 20 Co .5 C	150×10^3	90×10^3	250	30.5×10^6	0.308	7.8×10^{-6} (70°-200° F)	87 (approximate)	----
Discaloy (wrought)	25 Ni 1.8 Ti 55 Fe .6 Al 13 Cr .05 C 3 Mo .5 Si	157×10^3 (129×10^3 at 1000° F)	109×10^3 (87×10^3 at 1000° F)	[b]126	28.3×10^6	0.287	8.5×10^{-6} (70°-200° F) 9.1×10^{-6} (70°-600° F) 9.5×10^{-6} (70°-1000° F)	----------	----
Beryllium nickel (cast)	96.0 Ni 2.66-3.0 Be .66 Cr .50 C(max)	$100\text{-}120\times10^3$	$60\text{-}75\times10^3$	[b]200	$22\text{-}24\times10^6$	0.284	-------	----------	----
Beryllium nickel (solution annealed and heat treated)	96.0 Ni 2.66-3.0 Be .66 Cr .5 C(max)	$200\text{-}225\times10^3$	$190\text{-}210\times10^3$	[b]400	$25\text{-}28\times10^6$	0.291	-------	----------	----

[a]For comparison with: SAE 52100 steel, 6.49×10^{-6} (77°-300° F); 18-4-1 steel, 6.60×10^{-6} (80°-400° F); molybdenum tool steels (M-10), 6.47×10^{-6} (78°-400° F).

[b]Measured value.

[c]Estimated, based on similar materials.

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TABLE II - WEAR, FILM-FORMATION, AND SURFACE-FAILURE PROPERTIES OF SEVERAL NICKEL ALLOYS

	Load (g)	Materials							
		"L" nickel	Beryllium nickel (cast)	Beryllium nickel (heat treated)	Inconel (cast)	Nimonic 80	Inconel X	Refractalloy 26	Discaloy
Relative amount of total wear volume as ratios of total wear volume for "L" nickel	50	1.0	13.2	5.7	3.2	1.6	5.6	5.9	5.6
	269	1.0	4.9	3.3	0.6	1.3	1.9	5.9	3.6
Film-formation properties		Films formed readily; film spalled at high loads	Nonuniform films formed	Nonuniform films formed	Films formed readily and did not break down with increased loads	Generally uniform film formed readily	Generally uniform films formed at heavier loads	Nonuniform film at light loads; noncontinuous films at heavy loads	Nonuniform films formed
Surface-failure properties		No welding; excessive plastic deformation at high loads	Some welding and metal transfer to disk specimen	Some welding and metal transfer to disk specimen	No evidence of surface failure	No mass metal transfer	Slight metal transfer	Some welding and metal transfer to disk specimen	Slight metal transfer

TABLE III - COMPARISON OF SURFACE CONDITIONS OF SPECIMENS

[Where surface photos are not included, the surface appearance of the specimens after various experiments may be considered approximately represented by the figures listed.]

Experiment	Materials							
	"L" nickel	Beryllium nickel (cast)	Beryllium nickel (heat-treated)	Inconel (cast)	Nimonic 80	Inconel X	Refractalloy 26	Discaloy
	Figure							
Rider specimen, 50-g wear run	5(a)	----	----	5(b)	5(c)	----	5(c)	5(c)
Rider specimen, 264-g wear run	6(a)	6(c)	6(c)	6(b)	6(c)	6(b)	----	----
Disk wear track, 269-g wear run	7(a)	7(c)	7(c)	7(b)	7(c)	7(c)	7(b)	----
Rider specimen, lubricated	9(a)	9(c)	9(c)	9(b)	9(c)	9(c)	9(c)	9(c)

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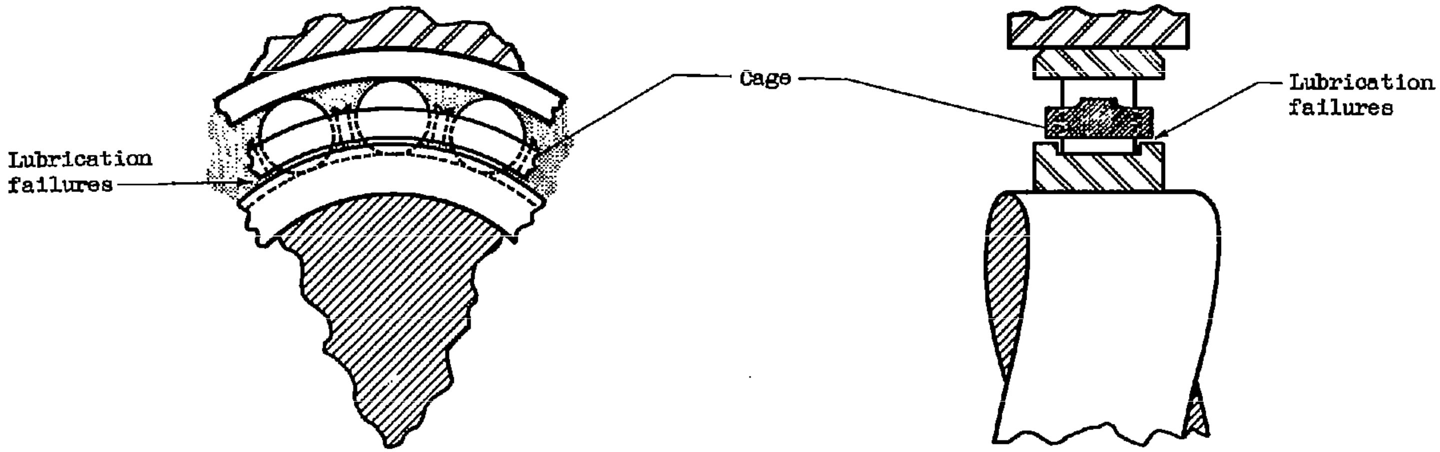
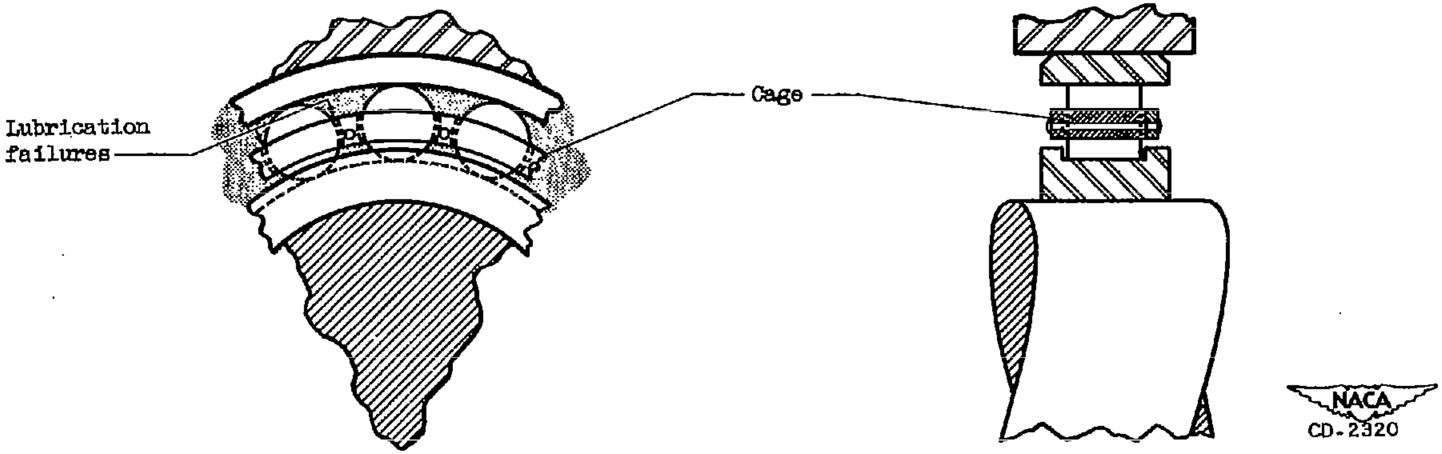
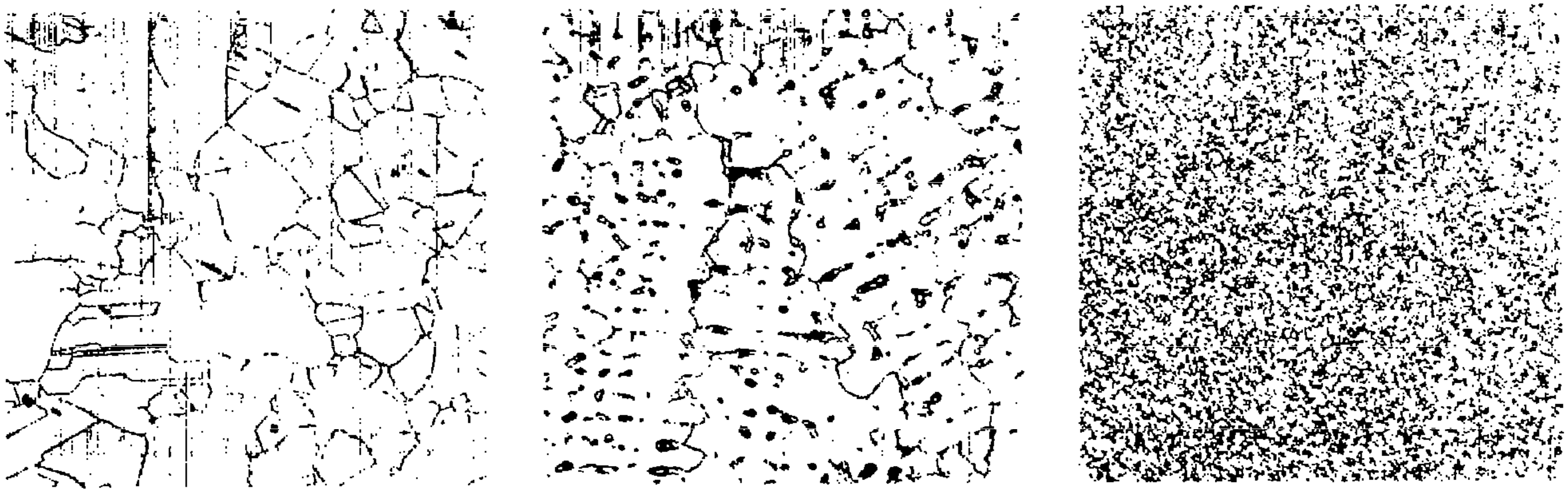


(a) Inner-race riding cage.



(b) Roller-riding cage.

Figure 1. - Location of lubrication failures at cage locating surfaces of rolling-contact bearings.



(a) "L" nickel; etchant, electrolytic oxalic acid.

(b) Inconel (cast); etchant, electrolytic oxalic acid.

(c) Inconel X; etchant, electrolytic oxalic acid.

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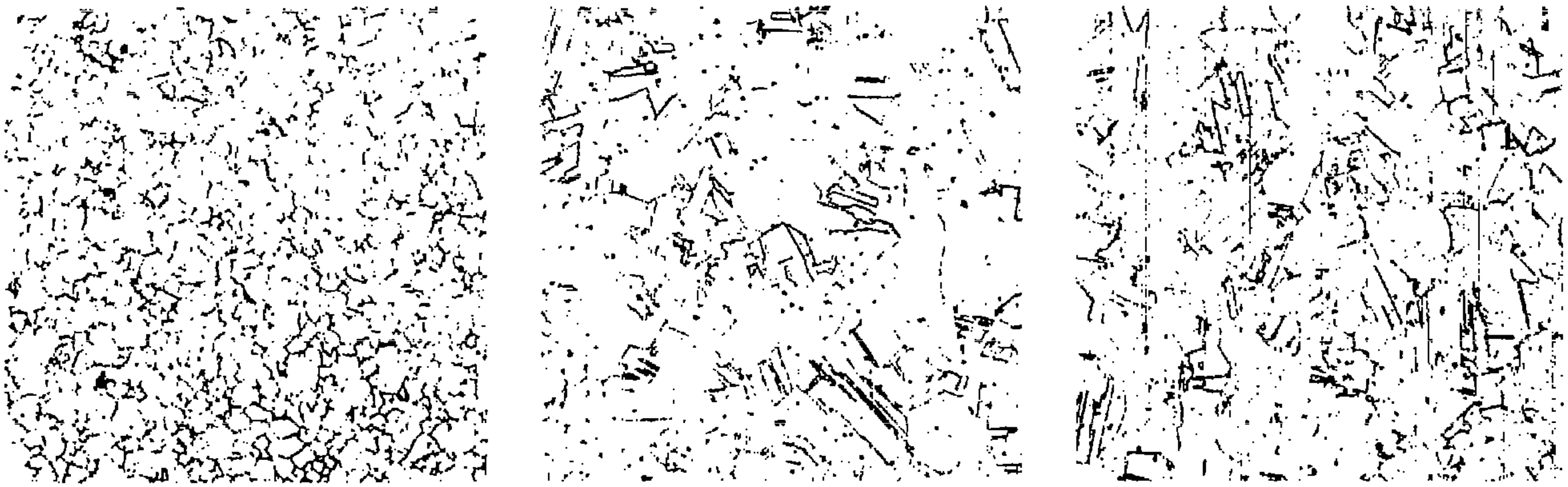
Figure 2. - Photomicrographs of metallographic specimens of nickel alloys used in wear and friction experiments. X100.



(d) Nimonic 80; etchant, electrolytic oxalic acid.

(e) Refractalloy 26; etchant, aqua regia plus cupric chloride.

(f) Discaloy; etchant, electrolytic oxalic acid.

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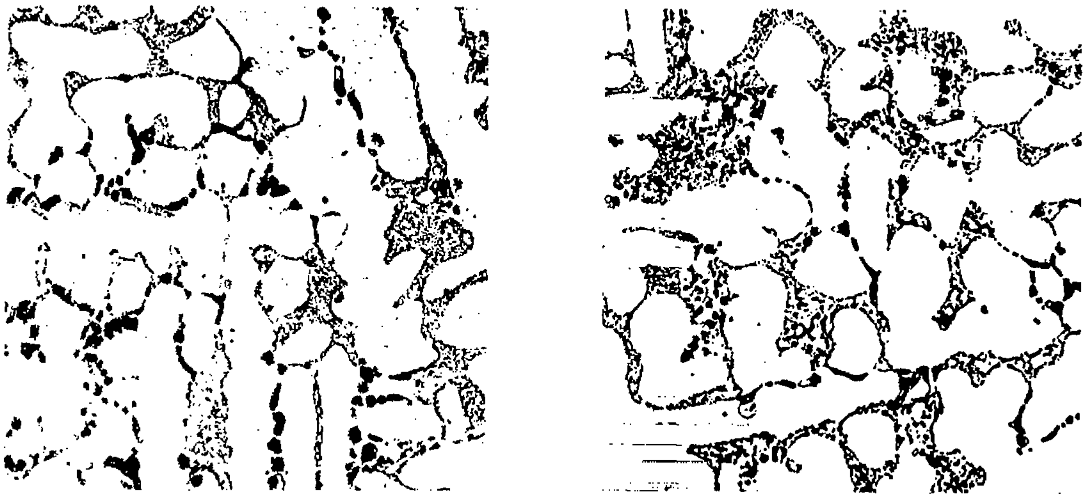
Figure 2. - Continued. Photomicrographs of metallographic specimens of nickel alloys used in wear and friction experiments. X100.



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(g) Beryllium nickel (as cast); etchant, electolytic oxalic acid.

(h) Beryllium nickel (heat treated); etchant, electrolytic oxalic acid.

Figure 2. - Concluded. Photomicrographs of metallographic specimens of nickel alloys used in wear and friction experiments. X100.

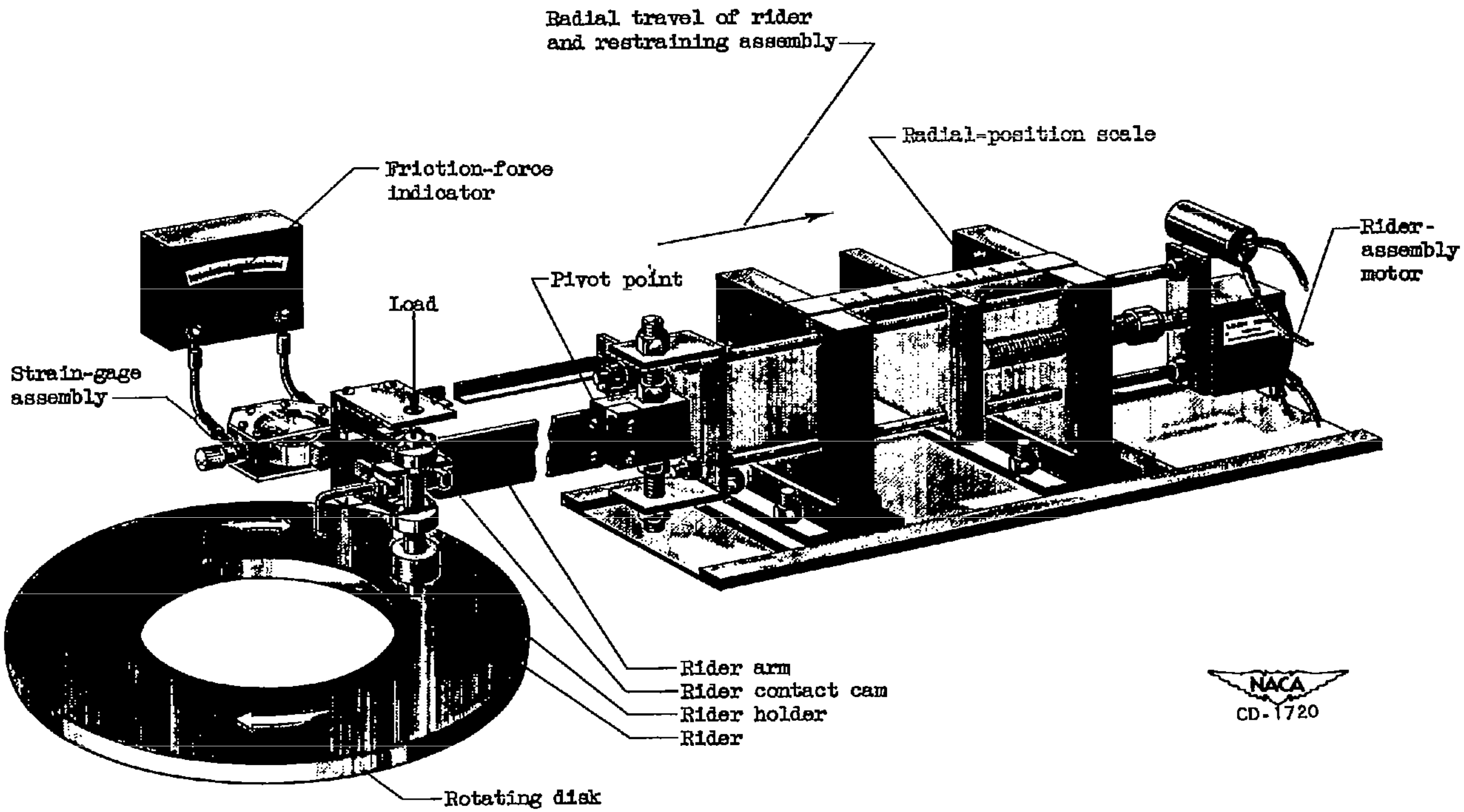
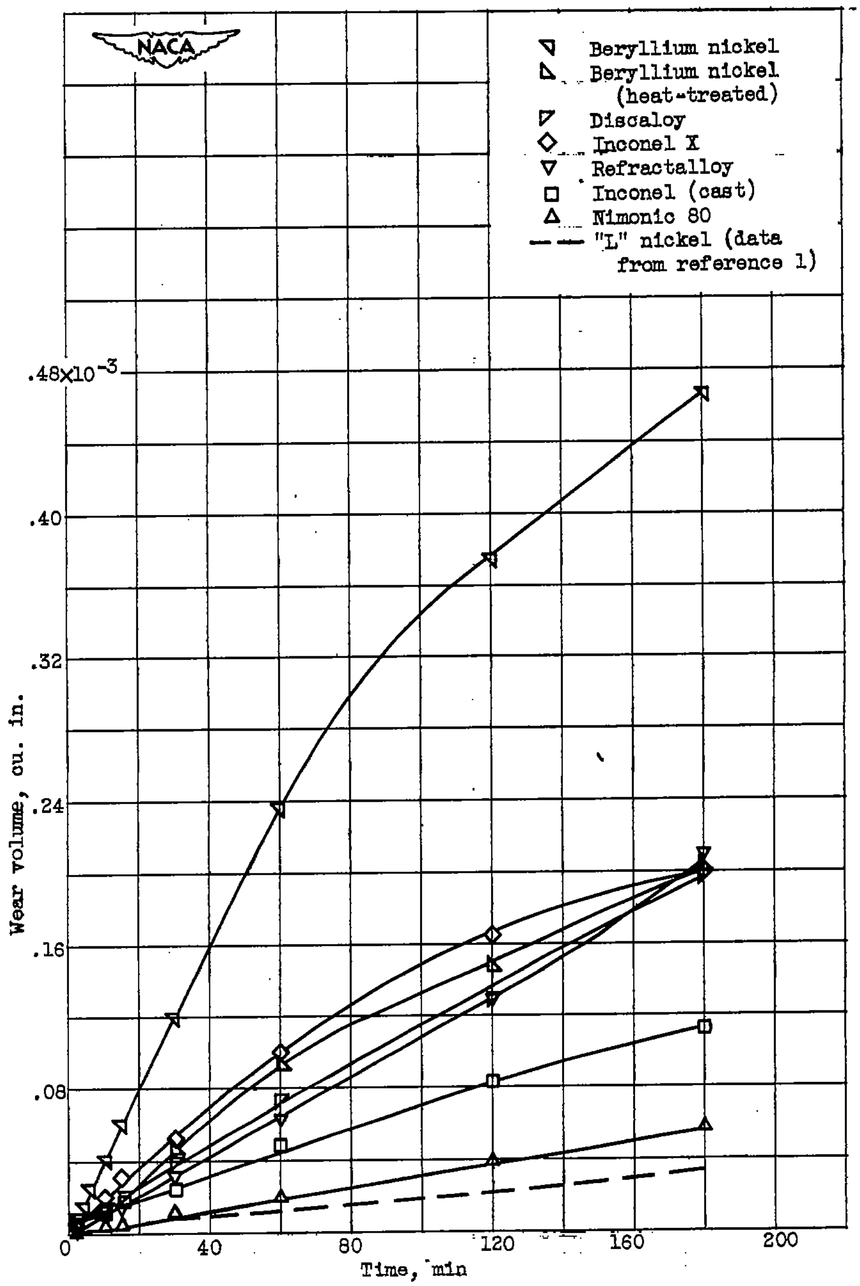
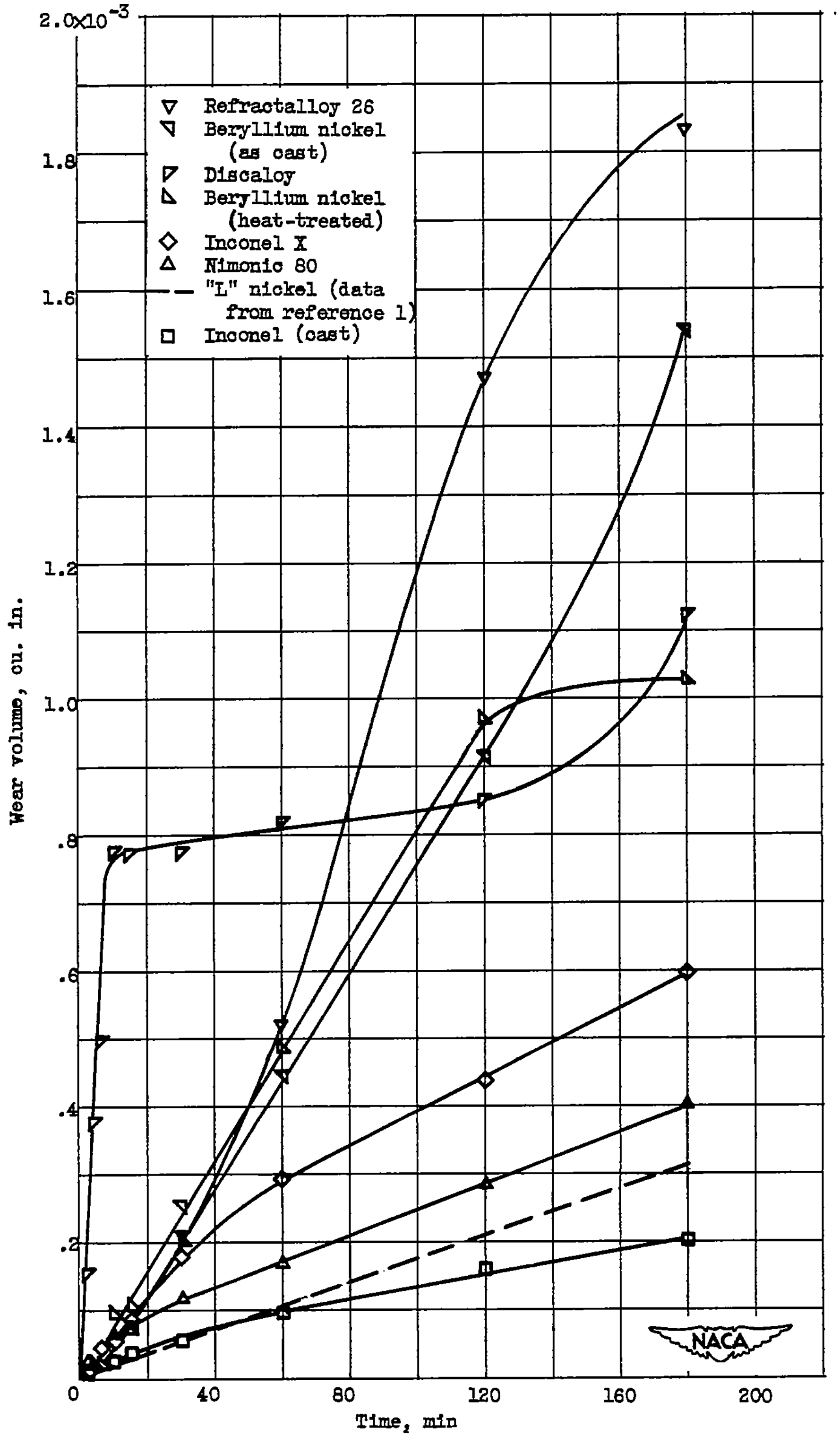


Figure 3. - Schematic diagram of sliding-friction apparatus.



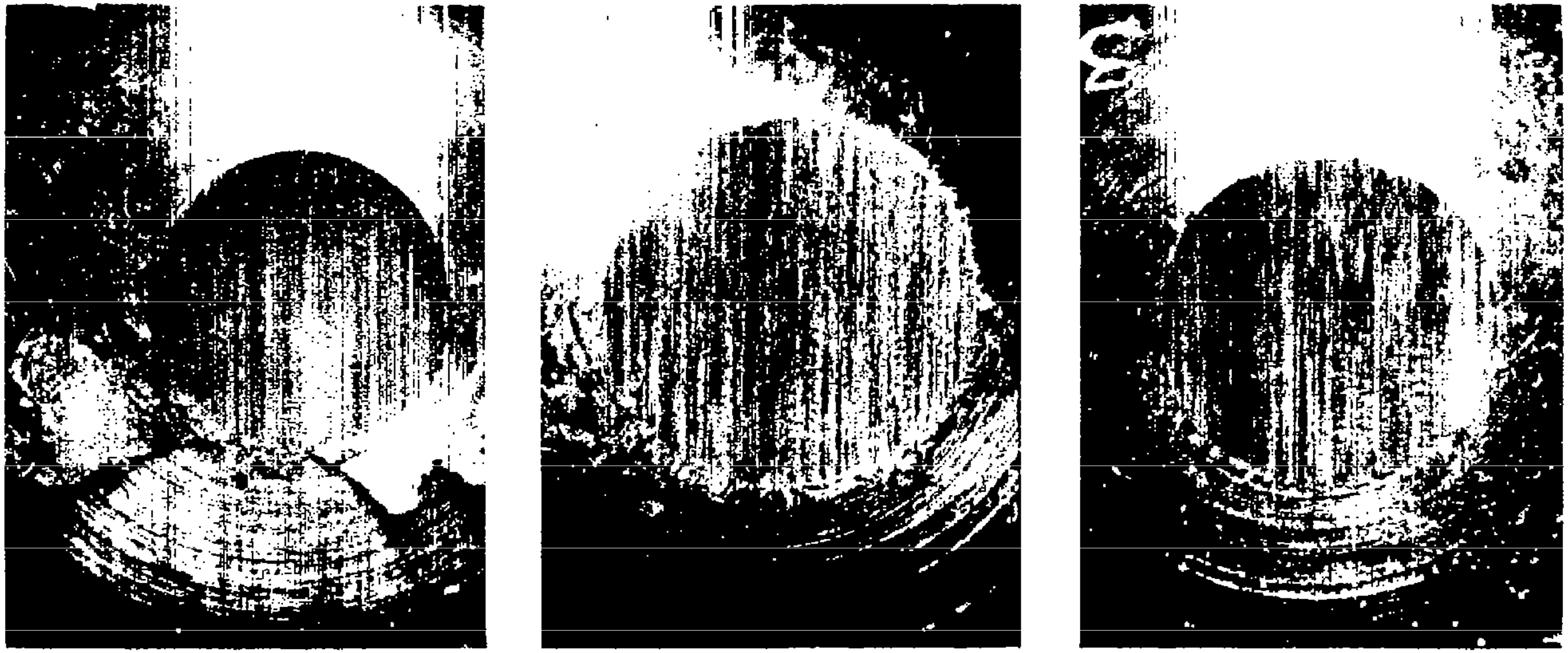
(a) Load, 50 grams.

Figure 4. - Wear of several materials sliding against hardened SAE 52100 steel. Sliding velocity, 5000 feet per minute.



(b) Load, 269 grams.

Figure 4. - Wear of several materials sliding against hardened SAE 52100 steel. Sliding velocity, 5000 feet per minute.



(a) "L" nickel. (b) Inconel (cast). (c) Nimonic 80.

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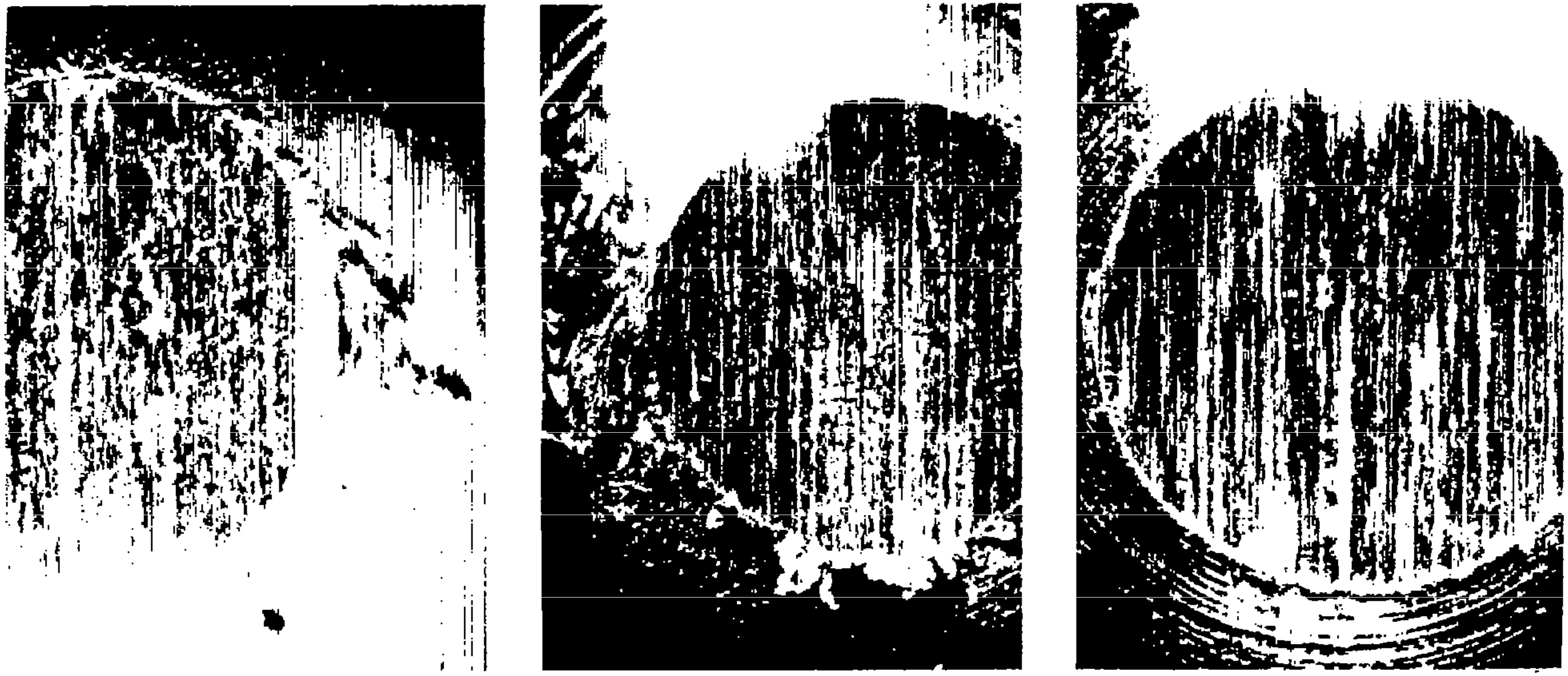
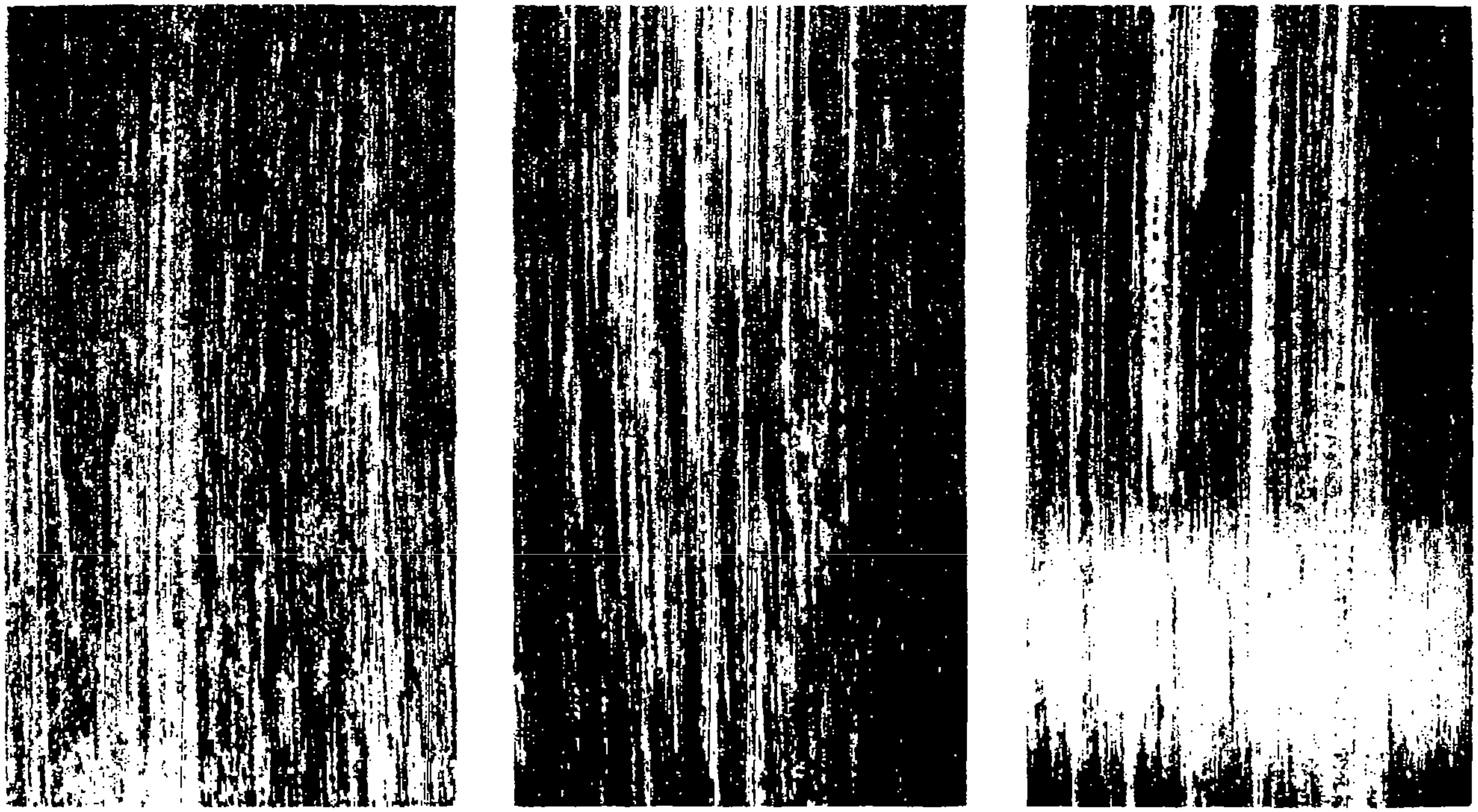
Figure 5. - Wear areas of rider specimens of various materials after 3-hour operation against hardened SAE 52100 steel without lubrication. Sliding velocity, 5000 feet per minute; load, 50 grams; X15.



(a) "L" nickel. (b) Inconel (cast). (c) Nimonic 80.

C-29828

Figure 6. - Wear areas of rider specimens of various materials after 3-hour operation against hardened SAE 52100 steel without lubrication. Sliding velocity, 5000 feet per minute; load, 269 grams; X15.



(a) "L" nickel. (Fig. 6(a) shows mating surface.)

(b) Inconel (cast). (Fig. 6(b) shows mating surface.)

(c) Nimonic 80. (Fig. 6(c) shows mating surface.)

Figure 7. - Wear tracks on disk specimens of hardened SAE 52100 steel after 3-hour operation using sliders of various materials without lubrication. Sliding velocity, 5000 feet per minute; load, 269 grams; X15.

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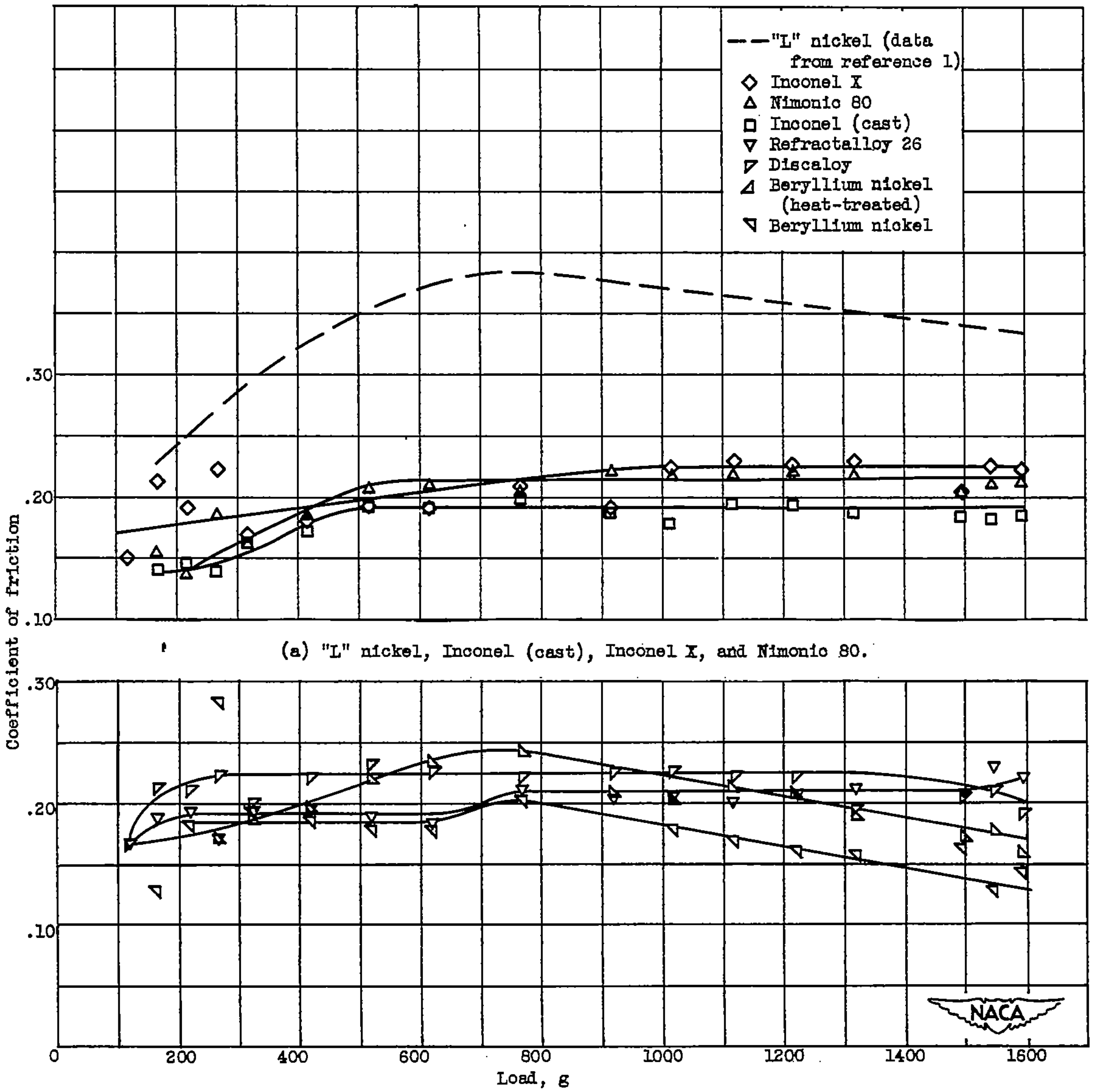
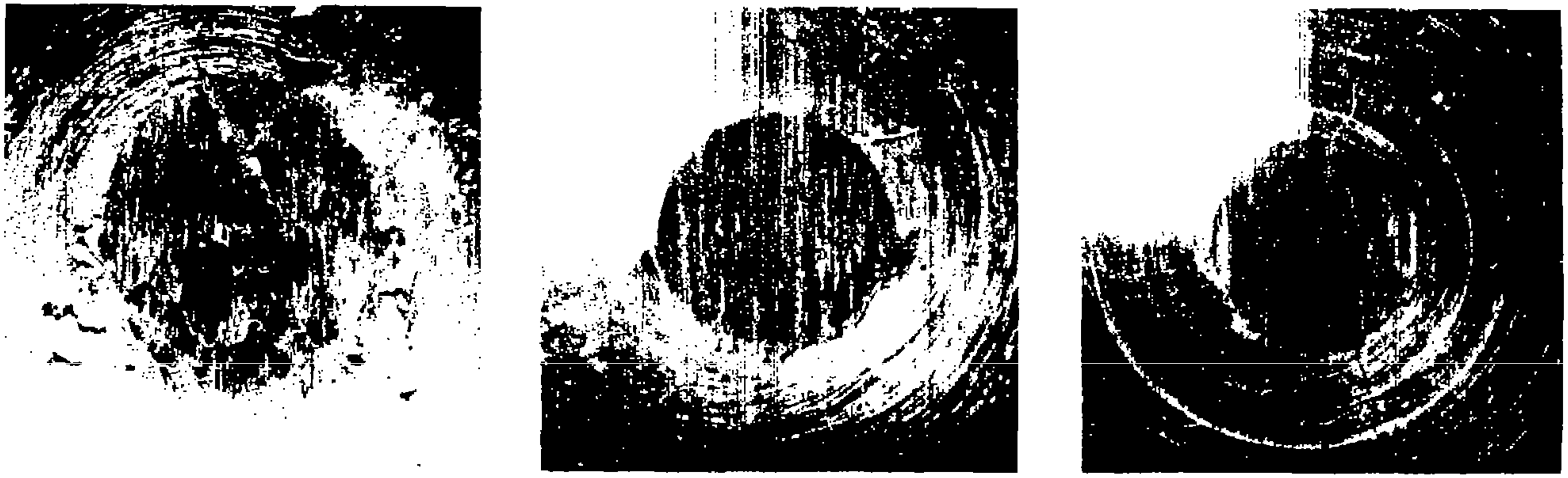


(b) Beryllium nickel, Beryllium nickel (heat-treated), Refractalloy 26, and Discaloy.

Figure 8. - Effect of load on friction of several materials sliding on hardened SAE 52100 steel boundary lubricated with grade 1005 turbine oil. Sliding velocity, 5000 feet per minute.



(a) "L" nickel.

(b) Inconel (cast).

(c) Nimonic 80.

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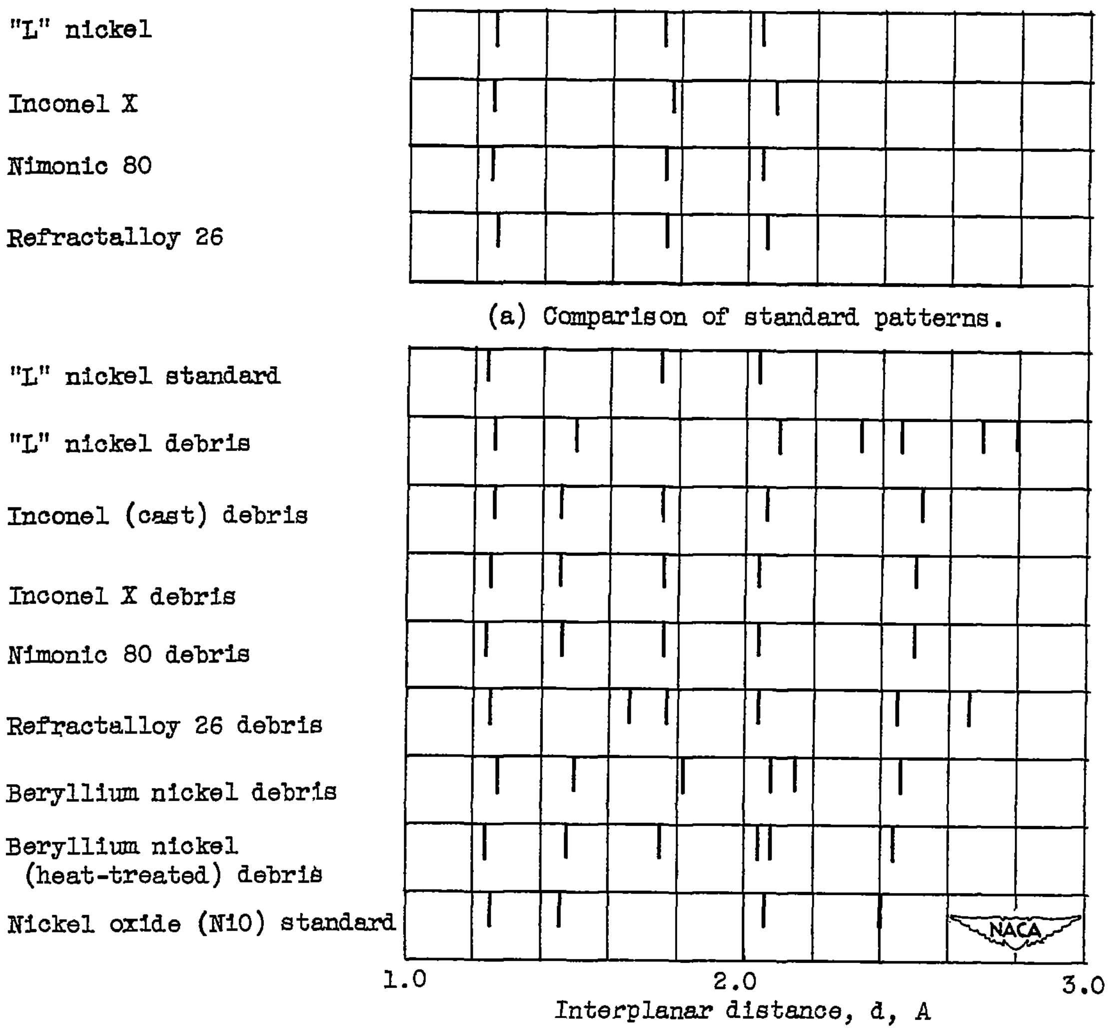
Figure 9. - Wear areas of rider specimens of various materials after similar series of friction experiments with hardened SAE 52100 steel boundary lubricated with grade 1005 turbine oil. Sliding velocity, 5000 feet per minute; load 119 to 1593 grams; X15.



(b) Comparison of patterns from debris with standard patterns from "L" nickel and nickel oxide (NiO).

Figure 10. - X-ray diffraction data for wear debris of nickel alloys run 3 hours in wear experiments with 269-gram load at sliding velocity of 5000 feet per minute; manganese radiation.